TMD DEFENSE PLANNING*

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Abstract

A key objective of Theater Missile Defense (TMD) is to defend multiple assets spread over a wide theater, simultaneously threatened by numerous missiles. To counter such scenarios, BM/C^3 is decomposed into the Battle Management and Defense Planning problems. The objective of Battle Management – analyzed in previous studies – is to assign weapons and sensors to minimize total damage as the battle unfolds in real-time, while the objectives of Defense Planning are to evaluate the effectiveness of specified defense designs against given attack scenarios, and determine improved interceptor launcher and sensor plans. This study focuses on the TMD land-sea based Defense Planning problem where multiple Theater Ballistic Missiles (TBM) and Theater Cruise Missiles (TCM) are launched from numerous missile threat origins (MTO) against many assets, and are countered by upper tier (UT) and lower tier (LT) sensors and weapons located at different sites. Models were developed for threat, sensor, weapon, area MTOs and assets, attack and defense plan generation, defense plan evaluation – including battle space analysis, damage score assessment and interceptor inventory distribution – and desirable defense plan generation. These models were then prototyped, integrated, and simulated in a rapid prototyping testbed. A number of attack and defense scenarios were simulated, and various measures of effectiveness evaluated, including engagement coverage, damage score, and interceptor inventory distribution. Modeling and simulation results, and some of the key performance characteristics are described.

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* Approved for public release; distribution is unlimited.

1. Introduction

The proliferation of TBM and TCM capabilities that go beyond the short-range tactical missiles has been on the rise during the recent past. And while theater missiles have ranges less than strategic, long-range missiles, nonetheless, their intermediate ranges have widened the scope and complexity of the TMD problem beyond that of tactical missile defense. To counter intermediate range TBMs, UT radars and interceptors of corresponding ranges have been developed. With intermediate range threats, sensors, and weapons, TBM TMD has, therefore, extended beyond the point defense capabilities of LT weapons and has evolved into a 4-dimensional (4D) space-time problem, with multiple shoot-look opportunities. This, together with denser threat environments competing for interceptor inventories, has rendered the shoot-as-early-as-possible point-defense approach obsolete for UT weapon systems. On the other hand, since terrain following TCMs fly at low elevation, they are detected fairly late by land-sea based systems, providing limited battle space – engagement timeline. Consequently, for land-sea based systems, LT (point defense) weapons are typically as effective against TCMs as UT weapon systems are against medium-range TBMs. Thus, the TMD problem to counter simultaneous multiple TBMs and TCMs of different ranges, threatening multiple area assets, using both UT and LT weapon systems is fairly complex. To this end, TMD BM/C^3 has two main components: Battle Management and Defense Planning.

The objective of Battle Management is to allocate sensors and interceptors with given locations and orientations to incoming

threats, minimizing leakage or damage to assets as the real-time battle unfolds. On the other hand, the objective of Defense Planning is to evaluate the effectiveness of a given defense design – a set of UT and LT sensor and interceptor launcher locations and orientations – to protect a specified set of assets against postulated TBM and TCM attack scenarios, and recommend more effective defense laydowns. From an overall weapon systems – sensors, weapons, and BM/C^3 – effectiveness perspective, the Battle Management and Defense Planning problems are coupled. It is indeed altogether possible that a sub-optimal laydown of defense elements that has not properly taken into consideration weapon system constraints or vulnerabilities, will render an otherwise robust overall weapon system ineffective during real-time battle. Conversely, the overall weapon system will perform effectively in real-time with a judicious placement of defense elements. Indeed, previous studies[1,2] demonstrated that the effectiveness of TMD Battle Management is primarily driven by the availability of battle space (engagement timeline), which is a function of engagement geometry, which, in turn, hinges upon Defense Planning, the focus of this study.

To analyze the TMD Defense Planning problem with some degree of realism, algorithms are developed in an integrated fashion to model the threats, sensors, weapons, area MTOs and assets, attack and defense plan generation, defense plan evaluation – including battle space evaluation, damage score assessment, and interceptor inventory distribution – and desired defense plan generation, which are described in section 2. Software prototypes for key algorithms are developed, tested, integrated, and simulated for a number of scenarios and defense laydowns in a rapid prototyping testbed to assess various measures of effectiveness (such as time on target, shot opportunities, and damage score), and to evaluate computational performance (throughput and memory) as briefly discussed in section 3. Finally, section 4 provides a few concluding remarks.

2. Modeling

Key TMD Defense Planning algorithms are briefly discussed in this section. There are a number of algorithm areas that are common to Defense Planning and Battle Management, in which case, references are made to [1] and [2] for a more detailed description. Threat, sensor, weapon, and MTO / asset models are discussed respectively in sections 2.1 - 2.4, followed by attack and defense plan generation models in sections 2.5 and 2.6. Defense plan evaluation algorithms are then discussed in section 2.7, including UT and LT weapon system evaluation, damage score assessment, and interceptor inventory distribution. Finally, section 2.8 provides an overview of the algorithmic approach to determine desirable defense plans. A number of alternative algorithms were modeled and prototyped in most all areas discussed, and disregarded in favor of the algorithms presented below. The models presented here were chosen due to their balance in computational performance, engineering effectiveness, accuracies, and simplicity. For purposes of this paper, Defense Planning is considered to be a process asynchronous to, and independent of Battle Management[1,2]. It is from this perspective, and in order to speed up the real-time execution of Defense Planning, that a number of sections are further broken out into off-line and real-time processing.

2.1 Threat Modeling

This section describes the methods to generate TBM and TCM trajectories, which are subsequently used to generate attack scenarios (section 2.5).

2.1.1 TBM Modeling

To alleviate the computationally intensive process of generating numerous trajectories needed for scenarios, a set of boost phase states spanning the theater are generated off-line for all threats. During real-time Defense Planning, the ballistic portion of the threat trajectories is generated incorporating effects such as launch point, earth rotation and oblateness.

Off-Line Processing

Using a 6-DOF trajectory generator with non-rotating earth, boost phase state vectors are generated at specified times for each TBM type, spanning its targeting range, and the theater altitude variation.

Real-Time Processing

In real-time Defense Planning, for a given TBM launch and intended ground impact point (GIP), trajectory states for a specified TBM type are determined as follows. First, the launch altitude and target range are determined. The off-line generated data is then utilized to determine boost states and times using bilinear interpolation, and transformed to account for oblate-rotating earth effects. The state at burnout is then propagated to the GIP using fourth order Runge-Kutta-Gill and related models as described in reference [1]. If the computed GIP is significantly different than the intended GIP, down-range and cross-range corrections are computed and the process is iterated until the intended GIP is reached within a specified tolerance.

2.1.2 TCM Modeling

Off-Line Processing

Terrain following/avoidance TCMs are assumed in this study. To this end, terrain data – such as a grid of latitude, longitude, and altitude – spanning the theater are generated off-line.

Real-Time Processing

In real-time, the objective is to determine the trajectory (i.e. the turn points) of a TCM, for a specified launch and impact point, terrain data, and data characterizing the TCM such as its heading variation, maximum range, maximum number of turn points, and minimum elevation above ground level (AGL) or above sea level (ASL). There are many techniques to solve this constrained optimization problem. However, the following heuristic approach was chosen for its simplicity. Starting with the launch point as the current point, connect it to the impact point. Determine the peak on this line and in its neighborhood, the local minimum altitude point satisfying the constraints. Choose the latter point as the current turn point on the trajectory, connect it to the impact point, adjust appropriate parameters, and iterate while satisfying the constraints.

2.2 Sensor Modeling

For purposes of this study, only ground and sea based phased array radars are assumed.

2.2.1 Upper Tier Sensor

The UT sensor is assumed to perform radar activities in support of TBM engagements with the UT interceptor.

UT sensor modeling concerning TBMs include: threat search fence assessment and determination, threat search detection time determination, search occupancy, and track accuracy determination. The latter two are discussed in references [1] and [2]. A brief description of search fence determination follows. For a given set of trajectories, radar location and orientation, and search elevation extent (typically a small band above the horizon), the range and azimuth extents of the search fence covering the given trajectories are determined: the trajectory portions within the elevation extents are determined, and their range and azimuth computed. The minima and maxima of the range and azimuth are then the extents of the search fence. This process can be iterated to subdivide a large search fence into smaller searches covering subsets of trajectories, thus minimizing sensor occupancy.

Following techniques similar to the ones discussed above and in references [1] and [2], UT interceptor trajectory states at specified times are verified that they are within the field of view (FOV) of the UT radar.

2.2.2 Lower Tier Sensor

LT sensors are assumed to perform radar activities in support of both TBM and TCM

engagements with the LT weapon. Thus, for TBM engagements, it is verified that the TBM is within the radar maximum range and FOV, intersected by the horizon. For TCMs, given the radar location and orientation, terrain data, and TCM trajectories and their AGL/ASL elevation, the threat detection contour is determined using techniques similar to those described in section 2.1.2. The detection contours are then used to determine the TCM detection times.

2.3 Weapon Modeling

2.3.1 Upper Tier Weapon

In order for the Defense Planner to assess engagements, it needs efficient methods to model the behavior of the UT weapon. The approach presented here is similar to the discussion in references [1] and [2].

Off-Line Processing

During off-line processing, Flyout Fans[1,2] (trajectory states) are generated spanning the theater and weapon firing parameters with specified granularity. The Flyout Fans are then used to generate the Intercept Tables which provide end-game parameters such as time of flight (TOF) to intercept, velocity at intercept, and loft angle for a given intercept point.

Real-Time Processing

In real-time, for given intercept states, the Intercept Tables are interpolated to determine the appropriate end-game parameters.

2.3.2 Lower Tier Weapon

Following the above concept, albeit using less complex models, the Intercept Table for the LT weapon is computed off-line spanning the weapon kill region with a specified granularity. The table provides TOF to given intercept points. In real-time, the TOF to a specified intercept point is determined by interpolating the values in the Intercept Table.

2.4 MTO / Asset Modeling

This section describes the modeling approach for point and area MTOs or assets. Airborne assets and weapon systems present somewhat different challenges. This study assumes ground and sea based assets and weapon systems only.

2.4.1 TBM Attacks

TBMs are typically launched from mobile launchers spanning an area MTO, with the possibility of targeting any point within an area asset. Thus, a traditional, brute-force approach in scenario generation might require too many trajectories spanning the MTO and asset areas, rendering computations too intensive and prohibitive. Luckily, the ballistic nature of TBMs allows the capability to model their trajectories fairly accurately, which then allows to model a set of trajectories uniformly distributed within a tube, with a mean trajectory and its corresponding moments. Such a statistical approach is consistent with the Defense Planning concept, where attack trajectories are not precisely known.

To support the statistical approach in TBM scenario generation for area MTOs and assets, areas larger than a specified granularity are first subdivided into triangles (sub-MTOs and sub-assets). A uniform probability distribution of launch and impact is assumed within each such MTO or asset triangle respectively. For each triangle, the centroid and the second moments about it are determined off-line, which are then used in Attack Plan Generation, section 2.5. Additional asset parameters are also introduced such as hardness to account for damage effects used in Damage Score Assessment, section 2.7.3.

2.4.2 TCM Attacks

Assuming scenarios with only ground and sea based assets and sensors, a number of factors influence MTO / Asset modeling for TCMs. One such consideration is the behavior and capability of TCMs. Thus, while launch conditions of a TBM typically provide significant information to predict its intended GIP, only the last few turn points of a TCM may provide meaningful information to predict its intended GIP. Furthermore,

because of their low AGL elevation flight, TCMs are typically detected late in their trajectory by ground based sensors, at which time their intended GIP may be determined fairly precisely. Consequently, TCMs are modeled point-to-point; that is, from a point MTO to a point asset, such that the spatial extent, if any, of MTOs or assets do not require additional modeling capability. This is consistent with the TCM concept of precision, surgical threats targeting point assets. Consequently, for TCM attacks, MTOs and assets are assumed as points, iterating the point-to-point approach to span area assets if necessary.

2.5 Attack Plan Generation

In a general Defense Planning problem, weapon system constraints affected by time of year and day are relegated to second order effects and are not considered in the initial phase, such as discussed here. Thus, absolute time is not considered in scenario generation. Instead, all times are relative to threat launch times – time after launch (TAL).

2.5.1 TBM Attack Plan Generation

For each TBM type, targeting pairs from MTOs to assets are first determined by performing a crude range check, and for the eligible pairs, trajectories are then generated as follows. Note that, as discussed in section 2.7, Defense Plan Evaluation, metrics such as time on target (TOT) or shot opportunities, are assessed as averages over the trajectory tube from a sub-MTO to a sub-asset. Such a statistical computational technique entails a statistical representation of the MTOs and assets in terms of their centroids and second moments, and a corresponding statistical representation of the trajectories. The latter is represented by the mean trajectory from sub-MTO centroid to sub-asset centroid, and ten other trajectories with a specified granularity around the centroids, to model the differentials in the Hessian matrix (see section 2.7.1) as differences. Other TBM parameters are also considered such as warhead type, TBM inventory, and launch rate which affect Damage Score Assessment and Interceptor Inventory Distribution (section 2.7.3).

2.5.2 TCM Attack Plan Generation

As discussed in sections 2.1.2 and 2.4.2, TCMs are considered precision threats, and their trajectories are considered from a point MTO to a point asset. Thus, the many-on-many MTO to asset scenarios are generated repeating the point-to-point trajectory generation algorithms as necessary.

2.6 Defense Plan Generation

The user can place the UT and LT weapons in any configuration and the Defense Plan Evaluation process (section 2.7) will provide a commensurate assessment. However, to achieve effective defense plans, this section provides some heuristics to initiate the Defense Plan Generation process at reasonable points using graphic tools discussed in section 3.

2.6.1 Upper Tier Weapon

It is assumed that the UT sensor and weapon launcher do not have to be collocated.

Considering the radar cross section (RCS) of the TBMs at the given MTOs, the location and orientation of the UT sensors are chosen such that the MTOs are within range of the 2D radar footprint, and the high traffic corridors of the TBM trajectories are covered. Search fences are generated as described in section 2.2.1, although any search fence input by the user can be assessed.

The UT weapon launcher locations are chosen such that they are comfortably within the FOV of the sensors, and spread cross-range from the threat trajectories while satisfying constraints such as communications link.

2.6.2 Lower Tier Weapon

It is assumed that the LT sensor and weapon launcher are collocated. Since it is also assumed that TCMs can only be engaged by the LT weapon, their location and orientation are chosen such that they protect high value assets threatened by high traffic

TCM corridors, detecting the threats as early as possible.

2.7 Defense Plan Evaluation

For the given Attack and Defense Plans, Defense Plan Evaluation is performed in a modular fashion, progressing to a subsequent phase after obtaining a satisfactory solution at a given step. The following is a nominal Defense Plan Evaluation sequence. Other sequences can also be exercised, provided that data needed from another step is available. If at a given step an unsatisfactory evaluation is obtained, then the Defense Plan is appropriately modified and the evaluation iterated. Graphic tools are utilized to aid the evaluation process.

2.7.1 Upper Tier Weapon

The UT weapon system is assessed for Threat Search Fence Evaluation, Interceptor Acquisition Evaluation, and Battle space Evaluation.

Threat Search Fence Evaluation

Threat search fences are evaluated for detection coverage, detection times, and occupancy. Thus, whether a given search fence covers all the threats that it was intended to detect is determined, and the corresponding detection times. Radar occupancy for each search fence, and the total occupancy due to searches for each radar are also computed.

Interceptor Acquisition Evaluation

As discussed in section 2.2.1, UT weapon launcher locations are evaluated to determine whether the interceptors are within the FOV of the UT radars.

Battle Space Evaluation

For the given attack trajectories, defense plan, and the corresponding weapon Intercept Tables, the eligible threat engagement regions are determined satisfying weapon system constraints that meet single shot probability of kill thresholds. The engagement coverage so computed is made available for evaluation by the user for each sub-MTO sub-asset combination, and aggregated for each MTO-asset pair. The engagement regions computed earlier are also used to determine TOT, shot opportunities (rung count), and slack time (the amount of time by which an intercept can be delayed without losing a rung).

The kernel algorithm to determine engagement regions, TOT, and rung count uses the statistical representation of area MTOs and assets, and TBM attack scenarios discussed earlier. Thus, for each sub-MTO and sub-asset combination, the average TOT, for example, is computed by adding to the TOT of the mean trajectory (from the sub-MTO centroid to the sub-asset centroid) the products of the area second moments with the Hessian of the TOT of the corresponding trajectories, derived by taking the differences of the mean and the other ten trajectories discussed in section 2.5.1.

2.7.2 Lower Tier Weapon

The LT weapon is assessed for Threat Detection Evaluation and Engagement Coverage encompassing both TBM and TCM attacks. Hence, detection coverage is computed to determine if threats penetrate the radar FOV, and the corresponding detection times with the results made available for each sub-MTO and sub-asset combination, along with the aggregates for each MTO-asset pair. Finally, the LT weapon TOF from the Intercept Table (section 2.3.2) along with the threat detection time is used to determine eligible engagement opportunities, and made available to the user.

2.7.3 Damage Score Assessment and Interceptor Inventory Distribution

For specified attack scenarios, defense laydown, and theater-wide threat and weapon inventories, a worst case attack / best case defense battle is first generated. In such a battle, the attacker and defender both have full knowledge of the other side's capabilities. The attacker knows the Defense Plan and uses this knowledge to create a

worst case Attack Plan. The defender knows that the attacker will behave in this way and creates a Defense Plan which will minimize the effects of any worst case attack.

The Attack Plan consists of a threat inventory distribution and an attack strategy. The threat inventory distribution specifies how the TBMs and TCMs are spread across the MTOs, and the attack strategy specifies the expected number of threats that the attacker would launch from each MTO against each asset. Similarly, the Defense Plan consists of the distribution of interceptor inventories, and the defense strategy determines the expected number of interceptors that the defender should launch from each launcher site on each rung against the worst case attack. Such a mixed strategy game theoretic model is solved using specialized numerical integration algorithms[3] with linear programming techniques[4] to determine the expected damage score. The attack rate, together with the interceptor firing and reload rates can be used to determine the number of weapon launchers needed at each site.

2.8 Desirable Defense Plan Generation

The previous approaches are used to evaluate a specified Defense Plan against specified Attack Plans to protect given assets. The approach outlined in this section determines a desirable Defense Plan to protect given assets against specified Attack Plans. The kernel algorithmic approach can be used for either weapon launcher or sensor placement, or a combination of both, as long as the appropriate metrics are utilized. Possible metrics include: TOT, rung counts, slack time, damage score, or a heuristic weighted sum of any combination. One possibility is to assume the given radar laydown and to determine desirable weapon launcher locations.

2.8.1 Initial Templates

Using the techniques described in the previous sections, the specified metric is computed for each sub-MTO sub-asset combination spanning the whole theater with a given granularity. For the given sub-MTO and sub-asset combination, such a template (matrix) provides the value of the metric for the whole theater. The templates for all sub-MTO sub-asset combinations are then summed to obtain the aggregate template for the whole theater.

2.8.2 Determination of Desirable Laydown

The aggregate theater template is then used to determine desirable weapon system laydowns. Thus, if the problem is to determine desirable weapon launcher locations for a given sensor laydown, then the launcher location is varied across the theater, and metrics such as TOT and rung count are computed to determine the aggregate template. The values of the metric from this template are then used in an assignment algorithm to determine the desirable weapon launcher locations. The Maximum Marginal Return[5] (MMR) algorithm was used for its computational efficiency.

3. Prototyping and Simulation

The critical algorithms discussed in section 2, numbering well over one hundred, were prototyped in Ada, tested, and integrated in a rapid prototyping testbed, consisting of over 30,000 source lines of code (SLOC).

Simulations were performed for a number of attack scenarios, assets to be protected, and defense laydowns. Attack scenarios consist of TBMs and TCMs launched from both point and area MTOs, aimed at point and area assets with different values and hardness. The attack scenarios consist of different TBM types, some with longer ranges than others. The defense laydown consists of both UT and LT sites with multiple radars and interceptor launchers. A number of Defense Plans were simulated and their effectiveness evaluated. Some of the simulation results are graphically represented in figures 1 - 12.

Figures 1 and 2 depict the TBM and TCM Attack Plans respectively, with the TBM

targeting pairs from an MTO to all reachable assets represented by the first figure, while the second represents the TCM point-to-point trajectories from all MTOs to all assets on a terrain map. Figure 3 depicts the UT weapon system Defense Plan, representing the two-dimensional footprint of the radar FOV, the search fences, and the footprint of the weapon kinematic. And Figure 4 depicts the LT weapon Defense Plan, representing the footprint of the radar FOV and the weapon kinematic reach.

The remaining diagrams, 5 - 12, present Defense Plan Evaluation results. Thus, figure 5 represents TBM detection coverage by the UT sensor for each MTO and asset, with 'x' indicating no coverage, and 'o' indicating coverage. Figure 6 represents the occupancy of each search fence for the three UT radars, and figure 7 represents a 3D view of the intersection of the UT radar FOV and UT weapon kinematic reach. Figure 8 depicts the engagement timeline of a given TBM trajectory tube (from a sub-MTO to a sub-asset) and the shot opportunities by the UT and LT weapons. Figure 9 provides a summary of engagement coverage by both UT and LT weapons for all threats from all MTOs to all assets. Figures 10 and 11 are results of the Damage Score Assessment and Interceptor Inventory Distribution computations, with the former representing the asset value data, and the latter providing the UT and LT interceptor inventory distributions. Finally, figure 12 represents a template spanning the theater assuming two MTOs and two assets where the metric is the TOT of the UT weapon.

4. Conclusions

This is one of the first attempts to analyze the land-sea based UT and LT TMD Defense Planning problem against TBM and TCM attacks in an end-to-end integrated fashion. It has been modeled, prototyped, and simulated for various attack scenarios and defense configurations. Some of the key results of this analysis have been graphically presented. The algorithms developed have been demonstrated to be fairly effective against postulated scenarios. It is hoped that this study has taken a significant first step in providing models and graphic tools in analyzing the complex problem of Defense Planning. Further modeling and simulation effort is required in such areas as higher fidelity modeling of system constraints – such as communication – and single shot probability of kill, and determination of desirable, if not optimal, Defense Plans to name just a few.

Acknowledgments

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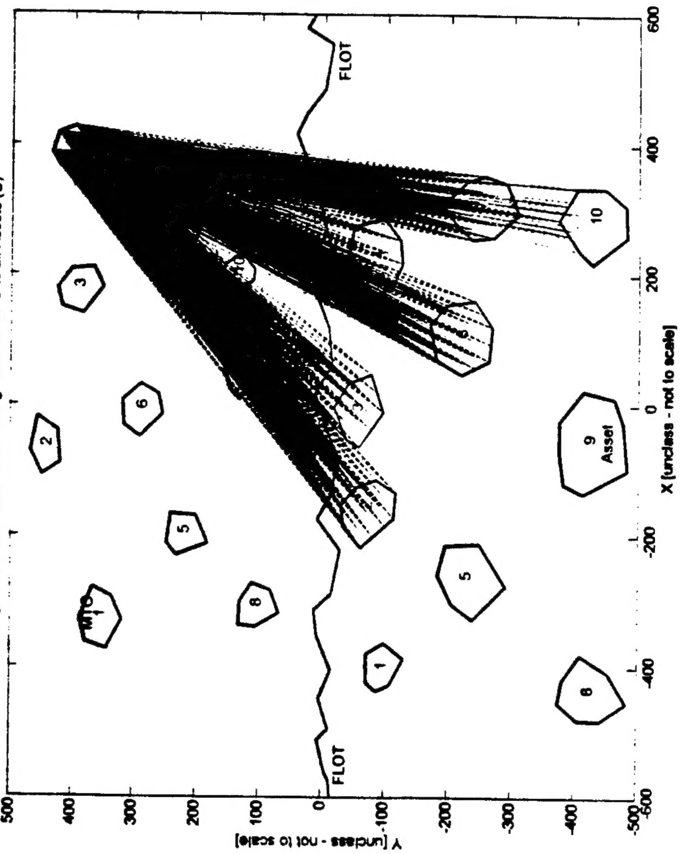

Figure 1: Valid TBM Attack Pairings from an MTO to all Assets (U)

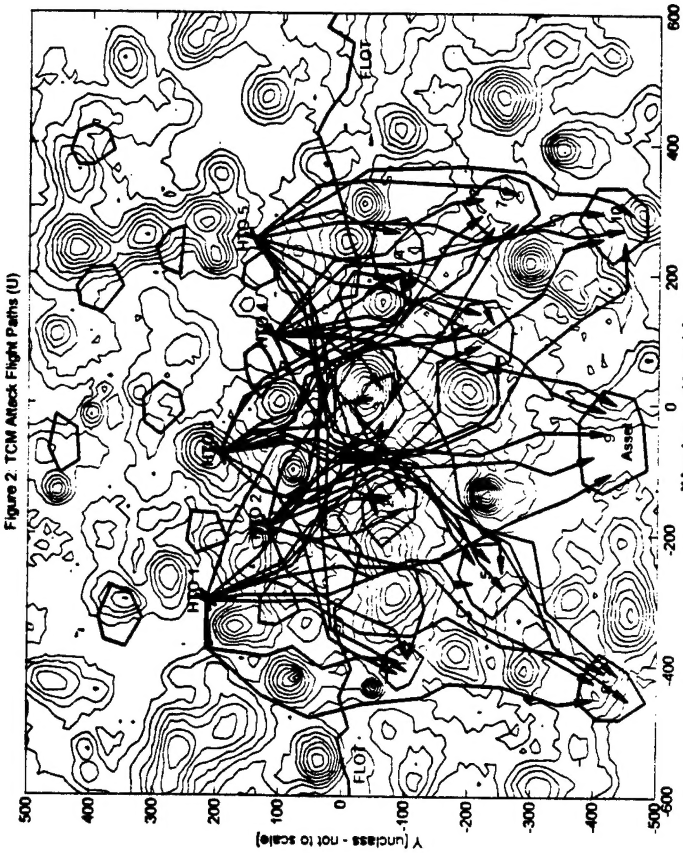

Figure 2: TCM Attack Flight Paths (U)

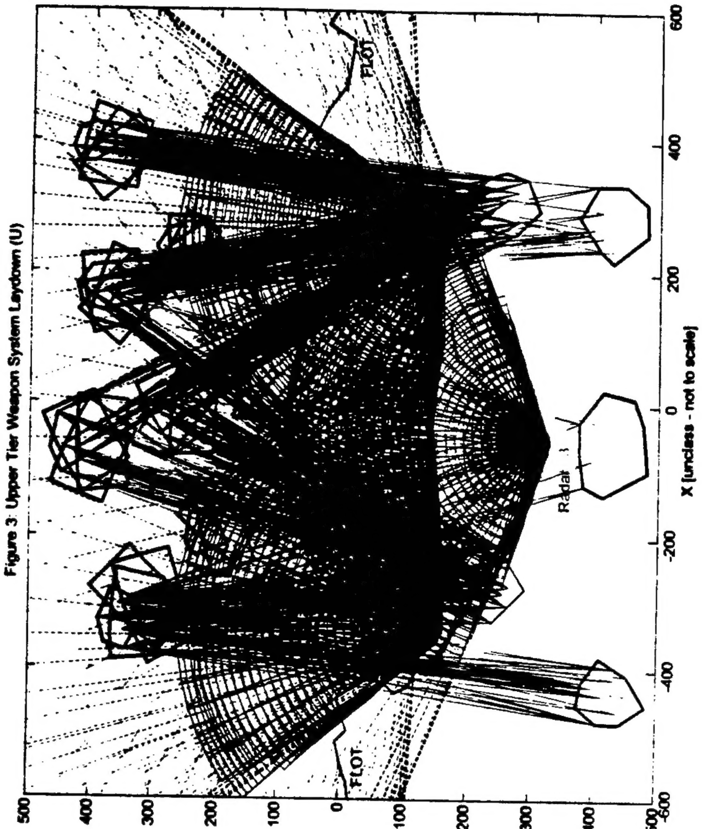

Figure 3: Upper Tier Weapon System Laydown (U)

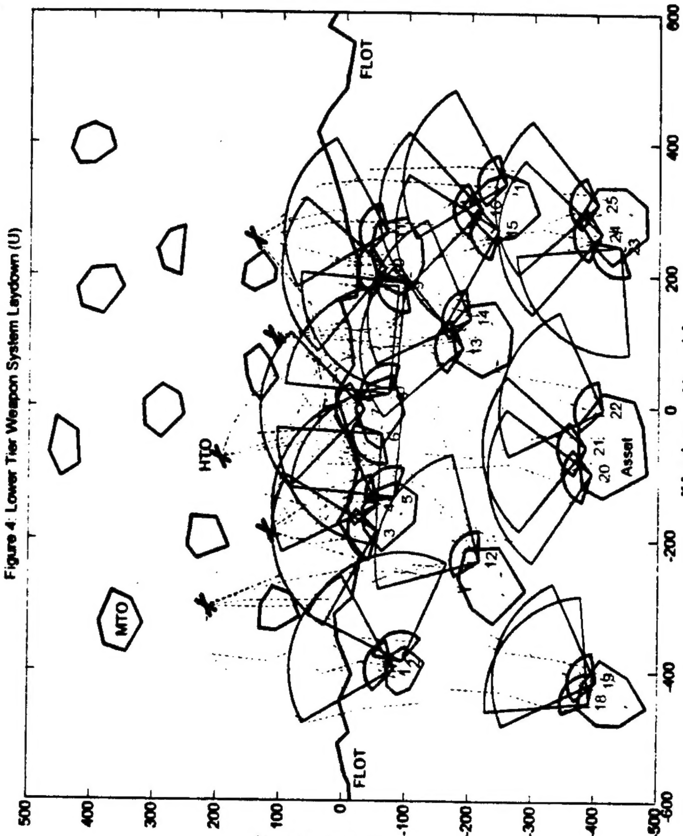

Figure 4: Lower Tier Weapon System Laydown (U)

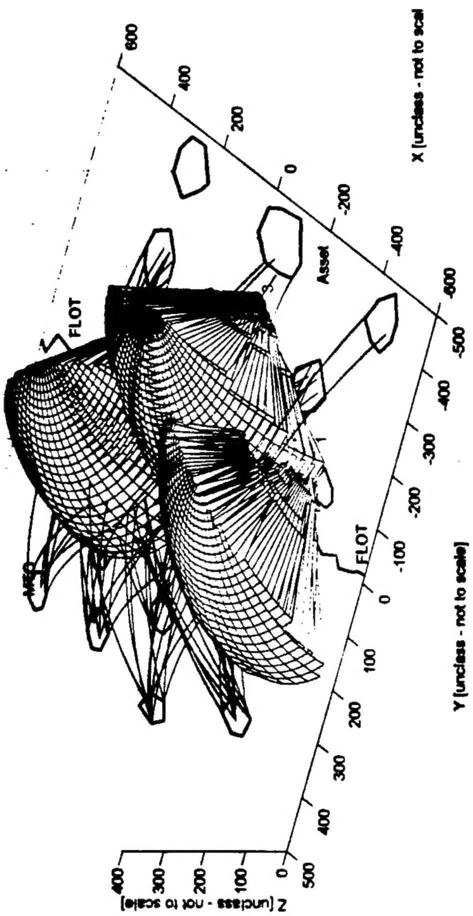

Figure 7: Upper Tier Weapon System Engagement Volume (U)

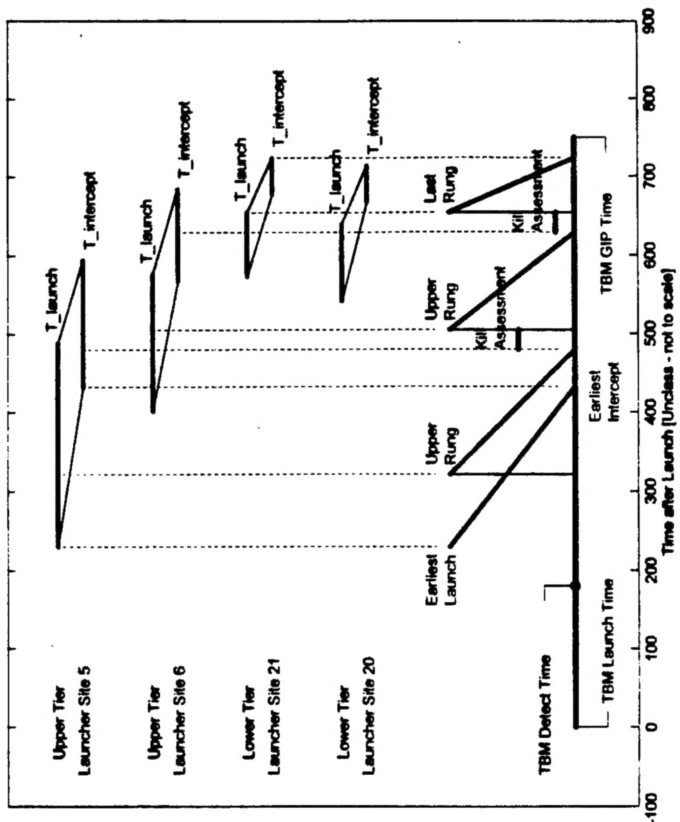

Figure 8: Single TBM Engagement Timeline (U)

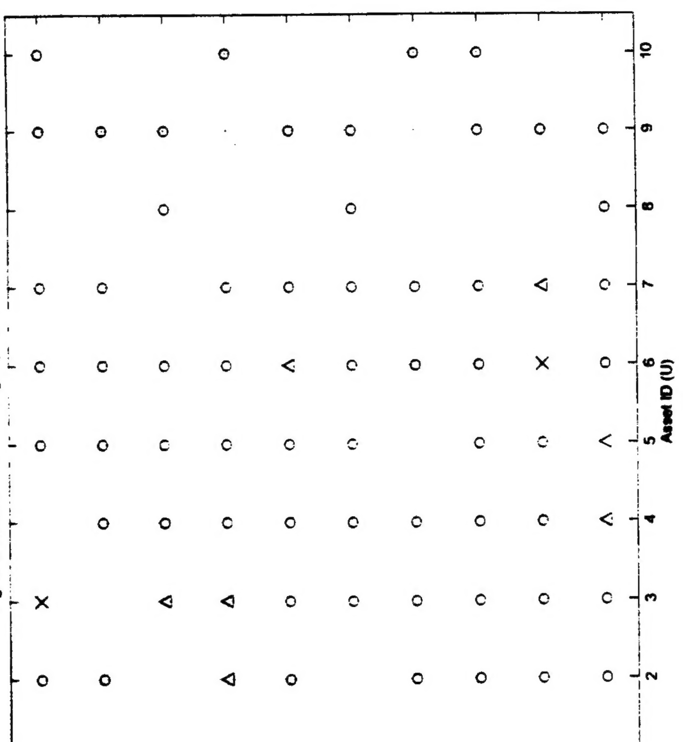

Figure 5: TBM Detection Coverage by Upper Tier Radar (U)

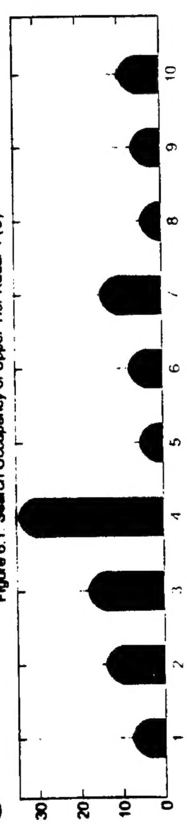

Figure 6.1: Search Occupancy of Upper Tier Radar 1 (U)

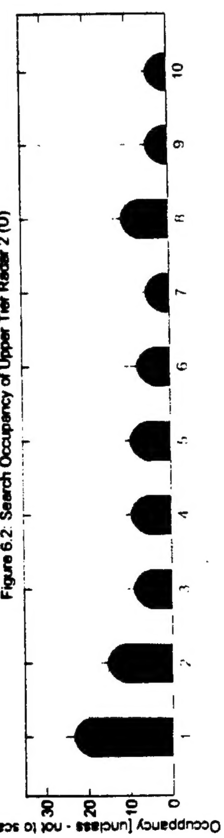

Figure 6.2: Search Occupancy of Upper Tier Radar 2 (U)

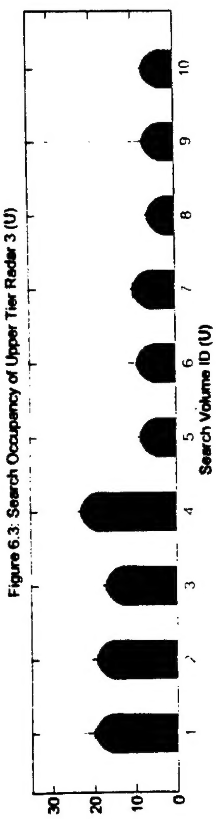

Figure 6.3: Search Occupancy of Upper Tier Radar 3 (U)

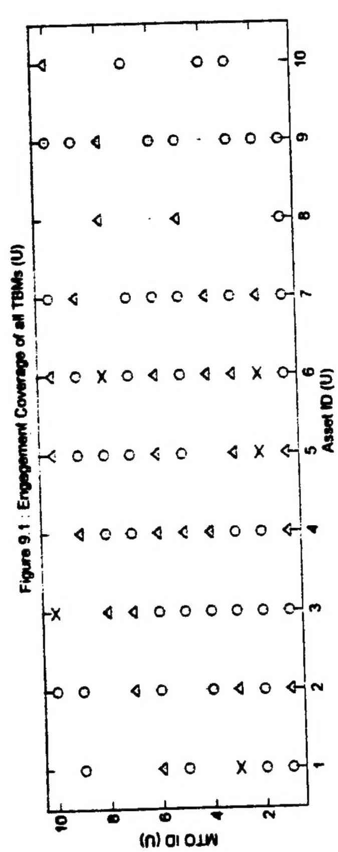

Figure 9.1 : Engagement Coverage of all TBMs (U)

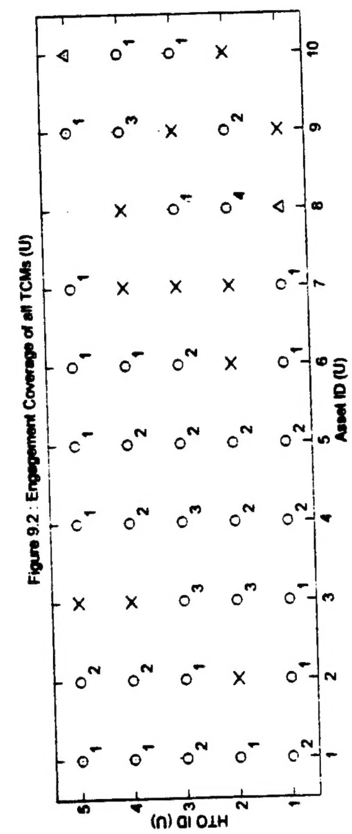

Figure 9.2 : Engagement Coverage of all TCMs (U)

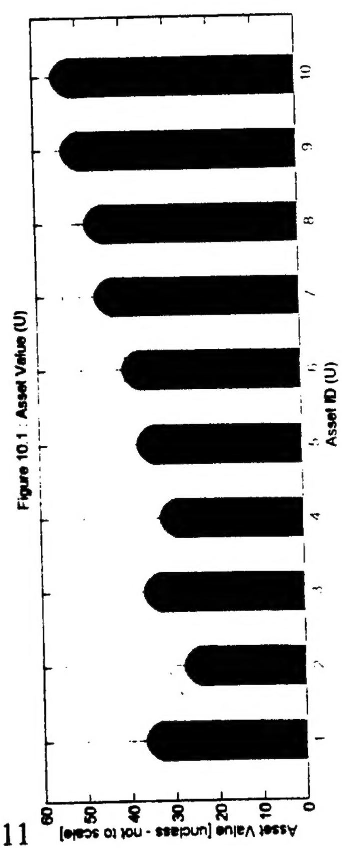

Figure 10.1 : Asset Value (U)

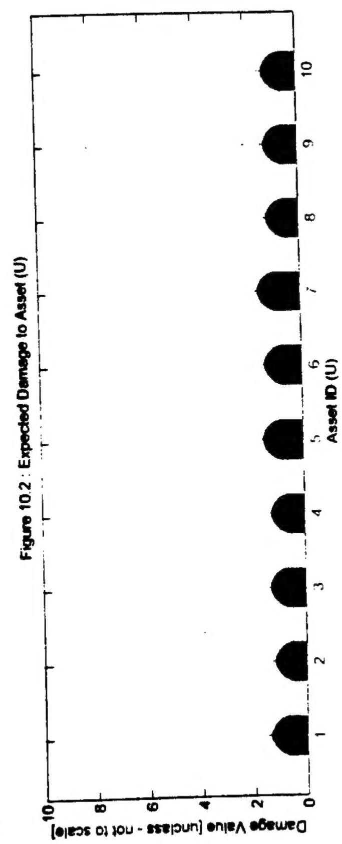

Figure 10.2 : Expected Damage to Asset (U)

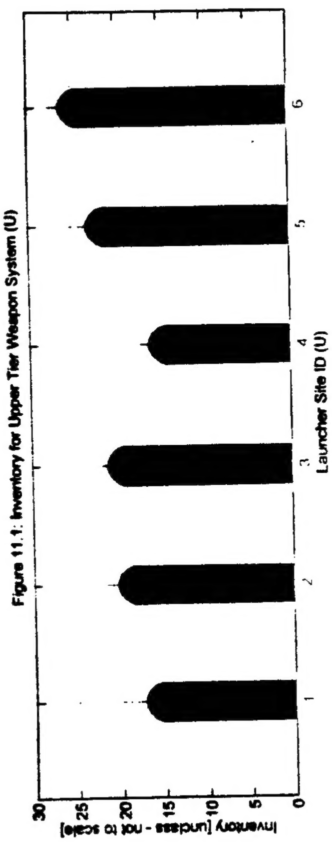

Figure 11.1: Inventory for Upper Tier Weapon System (U)

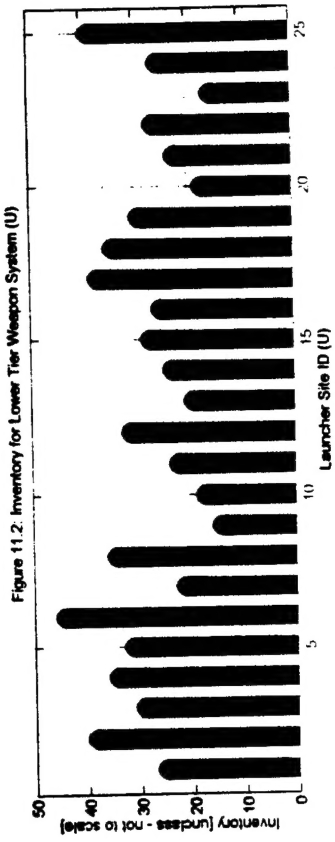

Figure 11.2: Inventory for Lower Tier Weapon System (U)

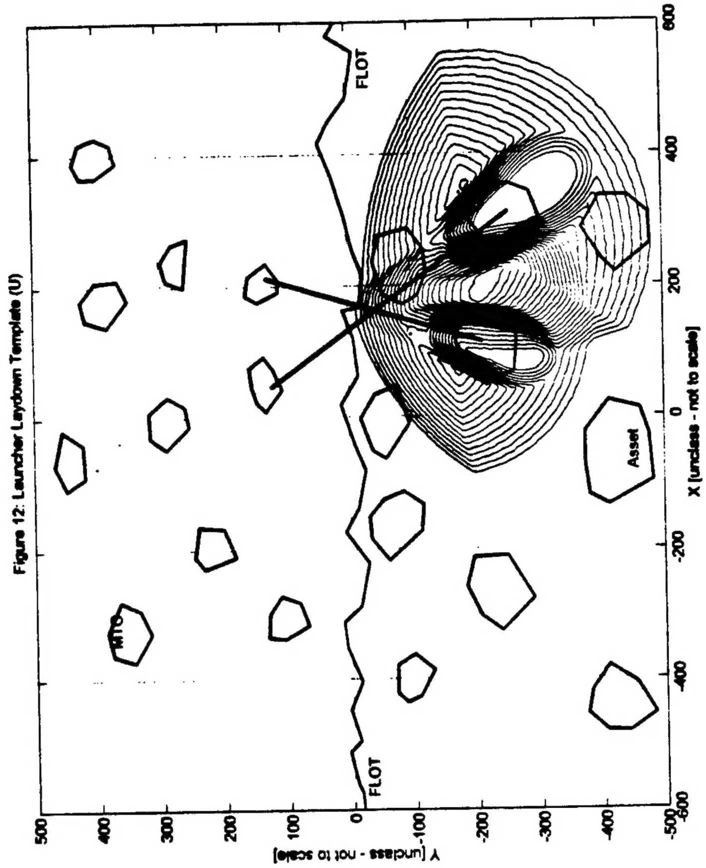

Figure 12: Launcher Laydown Template (U)

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